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DEVELOPMENT OF A CURVED CENTRE-CRACKED SPECIMEN FOR PRESSURE TUBE FRACTURE TOUGHNESS TESTING

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A.C. Wallace
Engineer

Nondestructive and Fracture Evaluation Section
Metallurgical Research Department

ABSTRACT

The design of a centre-cracked specimen that maintains tube curvature, and the associated testing grips are described. The results of finite element analysis and an elastic compliance calibration show that the linear elastic stress intensity factor (K_I) calibration is essentially the same as that for an equivalent-size flat plate specimen loaded in tension.

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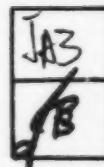
EXECUTIVE SUMMARY

A.C. Wallace
Nondestructive & Fracture Evaluation Section
Metallurgical Research

The design of a new type of specimen and grips for fracture toughness testing of pressure tube material is described. The specimen maintains the curvature of the pressure tube and permits testing of partial or fully through-wall axial defects. The curved geometry removes the need to flatten material for testing, making the specimen suitable for testing irradiated or hydrided materials. The centre-cracked geometry was chosen because it is most similar to the geometry of an axial crack in a pressure tube.

Both finite element analysis and an experimental elastic compliance calibration have been performed to determine the relationship between applied load, crack length and the linear-elastic stress intensity factor, K_I . The results show that the calibration is essentially the same as that for an equivalent sized flat plate loaded in tension.

The main features of the design and testing experience are outlined and the problems associated with extending the use of this specimen into the elastic-plastic regime are discussed.



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To

Dr. D. Mills
Director of Research

**DEVELOPMENT OF A CURVED CENTRE-CRACKED SPECIMEN
FOR PRESSURE TUBE FRACTURE TOUGHNESS TESTING**

1.0 INTRODUCTION

Recent pressure tube fracture research programs have placed increased emphasis on improving test methods. The observed decrease in toughness with increased neutron fluence, and concerns about possible increases in deuterium ingress and delayed hydride cracking growth rates have reduced the tolerable margins of uncertainty in estimates of the critical crack length (CCL) of Zr-2.5Nb.

Investigations have been mainly directed towards understanding the reasons for the discrepancy in predictions of fracture toughness from tests on large and small specimens. It is suspected that burst test liner effects and the dependence of the resistance curve shape on the size and geometry of small specimens are the primary factors responsible. The presence of size and geometry effects has been recognized for a considerable length of time and was one of the main reasons for initiating the program to develop the curved centre-cracked specimen.

Given the present situation, it may seem counter-productive to embark on the development of a new specimen when the problems with the existing ones are not fully understood. However, much of the work presented here predates the present controversy.

Thus, the primary intention of this report is to document the design and development of the curved centre-cracked specimen and the associated testing grips. First, the perceived advantages to testing with a curved centre-cracked specimen are described and the basic features of the design are explained. Second, the results of finite element analysis to determine the stress intensity factor calibration are described. Finally, the analytical results will be compared to the results of the experimental compliance calibration. It is anticipated that this information will be of interest to anyone involved with the fracture studies of CANDU pressure tubes, as well as to experimentalists concerned with the fracture properties of cylindrical or tubular components in general.

2.0 REASONS FOR DEVELOPMENT

There are basically three reasons for choosing a curved centre-cracked small specimen design. The first consists of the general advantages of using small specimens to obtain pressure tube critical crack length data instead of performing burst tests/1/. Small specimen tests are easier and less expensive to perform than burst tests and require considerably less material. Specimen and experimental characteristics can be changed more easily thus permitting a wider range of variables to be examined. In addition, data can be obtained from a larger materials base, thereby producing more statistically significant results.

The second reason - the requirement that the specimen retain the original curvature of the pressure tube - comes from the need to avoid flattening material to make specimens. The flattening operation reduces the wall-thickness of the specimen and introduces residual stresses that are not entirely removed by the subsequent stress relief operation, which is designed so as not to significantly alter the cold-worked microstructure of the pressure tube. These residual stresses probably have an effect on test results, and certainly make it difficult to prepare specimens having specific hydride structures.

In many instances flattening is simply not possible. Material removed from reactors, which may be embrittled due to irradiation or high hydrogen concentrations, would probably break if flattened. Even if flattening could be performed, subsequent stress relief operations would render further testing pointless by altering the hydride structure and annealing out irradiation damage.

The third reason for choosing this particular specimen is the fact that the centre notch is most similar to the type of defect generally encountered in a pressure tube. There is some evidence/2/ that the similarity in the crack geometry leads to predictions of critical crack length using resistance curve methods that are in better agreement with the results of burst tests than results obtained from compact tension specimens. (The relationships between J-resistance curves and small specimen geometry will be discussed further in Section 6.0). A centrally cracked specimen also offers an opportunity to investigate the behaviour of surface cracks and hydride blisters.

3.0 SPECIMEN DESIGN

The curved centre cracked specimen (Figure 1) is simply one third of the circumference of a section of pressure tube 60 mm long. A radial-axial starter notch is spark machined in the centre of the specimen and sharpened by fatigue. The specimen is pin-mounted to specially designed grips, through four holes that are drilled with the aid of a rotating jig (Figure 2). It is the grips that provide the key to testing the specimen by constraining it to deform radially and circumferentially in a manner approximating that of an internally pressurized tube.

3.1 Design of the Testing Grips

Figure 3 shows an unnotched specimen mounted in the grips. Referring to the side view in Figure 4, the grips consist of two interlocking sections, a, connected to the side plates, b, by pins, c. The specimen, d, is fixed to the grips by four pins through the L-shaped plates at e. When a tensile load is applied from the clevis

and pin assemblies, the two interlocking sections, a, will rotate slightly about their respective connecting pins, c, which act as pivot points. Because these pivot points are offset from the centre of curvature of the specimen, the curved surfaces of the grips, which initially follow the inside surface of the specimen exactly, push radially outwards on the inside of the specimen, constraining it to deform in a manner approximating that of a tube under increasing internal pressure.

The operation of the grips is demonstrated more clearly in Figures 5 and 6, which show the grips with the specimen removed. The curved surfaces of the mating grip halves consist of interlocking "fingers" that are initially closed (Figure 5) and open up as a load is applied (Figure 6). This motion effectively increases the length of the grip curved surface, although there are now some small gaps where the underside of the specimen is unsupported. This motion also increases the radius of curvature of the grip curved surface, and consequently that of the specimen. At this point, the radius of curvature is no longer uniform over the length of the specimen.

A computer analysis was performed to determine the precise shape of the curved surface for specified rotations of the grip halves. It was found that the variation in radius could theoretically be restricted to only a few hundredths of a millimetre at the largest expected test displacements by optimizing the location of the pivot points (c in Figure 4).

Figures 7 and 8 show computer generated plots of the displacement of the curved surface of one half of the grips for rotation angles of 0.8° and 5° . These plots were created as part of an analysis to optimize the position of the pivot points. In both figures, the lower curve represents the undeformed position. The upper curve gives the location of the grip surface and thus the shape of the specimen inside surface after a counterclockwise rotation of the specified angle. The displacement of the other half of the grips could be shown by reflecting these curves about the line $x = 0$, which corresponds to the plane of the crack in the specimen. The 5° rotation is probably the maximum that would ever be encountered in a test. Both figures show that the radial strain remains fairly uniform beneath the entire specimen, and thus the surface remains essentially a circular arc.

The basic concept behind the design of the grips was to somehow constrain the specimen to deform in the same manner as it would if it were part of a complete internally pressurized tube. Although the axial stresses cannot be simulated, analysis suggests that the circumferential stresses and strains can be very closely approximated. Further details on the analysis of the grips can be found in /3/.

4.0 STRESS INTENSITY FACTOR CALIBRATION

In order to apply this specimen in practical research situations it is necessary to be able to calculate both linear-elastic (K) and elastic-plastic (J) stress intensity factors as a function of applied load and crack size. There are two techniques available to do this, both of which were employed in this project. The first is an analytical approach using finite element methods. This has the advantage of being useful in both the linear-elastic and elastic-plastic regimes although it is sensitive to simplifications in the model and to numerical problems. The other available method is to perform an experimental compliance calibration. This can be an ac-

curate technique but is limited to use in the linear-elastic regime. The following sections describe in detail the application of both techniques to the elastic stress intensity factor calibration of this specimen.

4.1 Finite Element Analysis

The finite element analysis was performed using the MARC finite element code installed on the computer system at AECL's Chalk River Nuclear Laboratories. Precise details of the analysis technique can be found in /3/. Basically, the analysis was performed by applying displacement boundary conditions to the specimen mesh that were consistent with the deformation that would be imposed by the grips for a given applied load and rotation. Initially the mesh to be used in the analysis was generated as that of a flat specimen having dimensions in the same proportion as the curved specimen. Due to symmetry, only one quarter of the actual specimen was modelled. A total of 5 different meshes were generated to provide specimen normalized crack length ratios, $2a/W$, of 0.2, 0.4, 0.5, 0.6 and 0.8, where a is half the crack length and W is the specimen width (60 mm). Figure 9 shows the mesh for $2a/W = 0.5$. Different crack length ratios were modelled by laterally shifting the position of the crack tip. To perform the actual analysis, the coordinates of the nodes in these flat meshes were mapped onto corresponding coordinates for the curved geometry of the actual specimen. This is demonstrated schematically in Figure 10.

The analysis is based on prescribing the displacements of the specimen inside surface nodes, that is, those on the surface in contact with the grips. The problem becomes one of how to determine the displacements of these nodes precisely for a given rotation increment. To do this the assumption is made that the specimen nodes will displace along the curved surface in the same relation to one another as will occur in a flat specimen of the same size loaded in tension. Thus, specified displacements were applied to the loading pin-hole nodes of the flat specimen. For each increment, the corresponding displacements of all inside surface nodes were written to a tape file. By a complicated analytical procedure, analogous displacements were specified for the curved specimen inside surface nodes such that they lay on the curved surface corresponding to the grip surface after a rotation determined to produce the same increase in strain as the incremental displacement on the flat specimen. Thus the curved and flat specimen nodes always displaced the same relative amounts. By this technique, any possible effects of friction between the specimen and grips are ignored. However, these effects are believed to be small/5/.

The stress intensity factor, K_I , was calculated using the stiffness derivative, or virtual crack extension technique of Parks/4/. This is a simple and widely accepted method of calculating stress intensity factors by finite element methods, and a routine has been built into the MARC program for this purpose. Basically, this technique makes use the original definition of the J -integral by Rice/5/ as the change in potential energy corresponding to an increment in crack length or

$$J = dU/da \quad (1)$$

In the finite element case a potential energy change is determined by comparing the difference between the original solution and the solution where element stiffnesses within a user-defined contour are recalculated once the crack-tip element

nodes are moved by a small increment, to model an infinitesimal increase in crack length. The change in potential energy for the given crack length change can be directly related to the elastic strain energy release rate, G , and thus to K .

K values were calculated for two separate contour paths around the crack tip for each load-displacement increment in the analysis. The results from the two contours were in agreement to within 10% at the very worst.

4.2 Experimental Compliance Calibration

Compliance is defined as the amount of displacement produced in a body for a given applied load. The relationships between the elastic strain energy release rate, G , and compliance of a planar cracked body is given by:

$$G = \frac{P^2}{2B} \frac{dC}{da} \quad (2)$$

where:

- G = elastic strain energy release rate per crack tip
- B = thickness
- P = applied load
- C = compliance
- a = crack length

(Details of the derivation of this relation can be found in /3/ or in most introductory textbooks on fracture mechanics/6/).

To apply this to the curved centre-cracked specimen it is necessary to introduce a factor of 2 to the left hand side of (2) since there are 2 crack tips. Substituting normalized values of compliance (EBC) and crack length ($2a/W$) into (2) gives

$$G = \frac{P^2}{2WEB^2} \cdot \frac{d(EBC)}{d(2a/W)} \quad (3)$$

From the plane stress relation, $K = \sqrt{EG}$, this becomes

$$K = \frac{P}{B} \sqrt{\frac{1}{2W} \cdot \frac{d(EBC)}{d(2a/W)}} \quad (4)$$

Thus the procedure used to experimentally determine the stress intensity factor K , was to measure compliance for a range of crack lengths and to analytically obtain a polynomial relationship for normalized compliance (EBC) as a function of the crack length ratio ($2a/W$). The derivative of this function was then substituted into (4), permitting K to be evaluated for any load or crack length.

Compliance calibration tests were performed on 3 specimens with electron-discharge-machined starter notches 10 mm long. The specimens were fatigue cycled at constant load amplitude of between 0 and 50 kN at 1 Hz. At regular in-

Intervals of crack extension, compliance unloadings were performed by unloading from 50 kN to 37.5 kN. The relatively high loads were used to get maximum displacements but still not exceed the maximum load used for fatigue cycling. To reduce any frictional effects, the surfaces of the grips were coated with graphite.

Compliance was measured with an MTS extensometer modified so that contact with the specimen surface was made with two compass points. The contact points were approximately 4 mm above and below the crack at its centre. The extensometer was held in position with a mounting bar and two springs as shown in Figure 11. The extensometer output signal was amplified such that 0.5% of the total 8 mm displacement range gave a 10 V signal. A computer was used to automatically sample the signal via a 12 bit analog to digital converter giving a theoretical resolution on displacement of about 2×10^{-5} mm.

A total of 3 compliance unloadings were performed at each crack length, following which the specimen was heat tinted in a furnace for 10 minutes at 300°C to delineate the crack length at that point. The compliance was taken as the average of the 3 readings. Readings were obtained for about 6 or 7 different crack lengths on each specimen. Finally, the specimens were broken open and photographed, and the crack length for each heat tint band was measured from the photograph using a digitizer. Two typical specimens are shown in Figure 12 from which it can be seen that significant crack front curvature was present but that the crack growth was reasonably symmetric.

For analysis purposes, the compliance, C, was normalized using the measured thickness, B, of 4.1 mm and a value of 10^5 MPa for the modulus, E. The crack length readings, 2a, were normalized with respect to the specimen width, W, nominally 60 mm.

5.0 RESULTS

Values of K vs. applied load as determined from finite element analysis are given in Table 1 and plotted in Figure 13. For higher crack lengths and loads, the curves in Figure 13 become non-linear, reflecting the increasing plasticity in the ligament ahead of the crack tip. The normalized compliance data for the three specimens is given in Table 2 and plotted in Figure 14. Figure 15 shows the curve for the best 2nd degree polynomial fit to the combined data. Although higher degree fits gave lower sums of squares of residuals, the quadratic form was used because higher order fits gave improbable shapes to the curve outside the range of the experimental data. The resulting equation relating normalized compliance to normalized crack length is:

$$EBC = 0.173922 + 0.370214 (2a/W) + 2.24334 (2a/W)^2 \quad (5)$$

Differentiating this and substituting into (4) gives

$$K = \frac{P}{B} \sqrt{\frac{1}{2W} (0.370214 + 4.48668 (2a/W))} \quad (6)$$

For comparison, theoretical K values were obtained using the formula for a flat plate in tension/7/.

$$K = \frac{P\sqrt{\pi a}}{BW} \left(\sec \frac{\pi a}{W} \right)^{1/2} \quad (7)$$

Figures 16 to 20 plot K as a function of load according to: i) theory, by equation (7); ii) experimental compliance by equation (6), and; iii) the finite element results of Figure 13, for values of $2a/W$ of 0.2, 0.4, 0.5, 0.6 and 0.8.

6.0 DISCUSSION

Referring to Figures 16 to 20, it can be seen that the finite element and theoretical results agree reasonably well for all values of $2a/W$. The effects of crack tip plasticity can be seen in the finite element results, causing the curves to bend upwards at higher loads. This effect is more pronounced at larger crack lengths. In all cases, the finite element K values are slightly higher than the theoretical values at equivalent loads, even when the effects of plasticity are negligible. Although this difference is small enough to be accounted for by numerical inaccuracies, it may also be an effect of the curvature of the specimen. In the analysis of axially cracked cylinders, a curvature correction is introduced to account for a slight increase in crack tip stress intensity factor arising from curvature/8/. This correction becomes larger at longer crack lengths due to bulging of the material adjacent to the crack. However, since no bulging occurs with the curved specimen, this effect would not be expected to increase with crack length.

Compared to the finite element results, the K values obtained via the compliance calibration do not agree as well with the theoretical results. At lower crack lengths, the experimentally determined K values significantly exceed the values from flat plate theory while at larger crack lengths the theoretical values are underestimated. However, at intermediate crack lengths, with $0.5 < 2a/W < 0.65$, the agreement between the experimental and theoretical flat plate results is quite good.

At the longer crack lengths, part of the discrepancy is almost certainly due to error in the polynomial equation chosen to fit the experimental data. Figure 15 shows that beyond a crack length ratio of 0.7 the compliance increases quite rapidly while the best fit curve has a shallower slope. Had more data points been obtained in this range or a higher degree fit been applied, the fitted slope would have been steeper and equation (6) would probably have given better agreement with the flat plate theory.

At lower crack length ratios it is possible that some error has been introduced by the curvature of the crack fronts. It is possible that the compliance of a specimen with a straight crack front is less than that of a specimen with a skewed crack front of equivalent average length. This would explain the overestimates of the theoretical K values. If so, it is reasonable to presume that the results of the finite element analysis, for which the crack front was straight, give a fairly accurate description of the response of the specimen.

The uneven crack fronts observed in the experimental compliance specimens must be due to through wall stress variations. It appears likely that a bending stress is imposed on the specimen due to slackness in the fitting of the specimen on the grips. Load-displacement traces with the extensometer attached indicated that the outside surface of the specimen actually goes into compression briefly before returning to tension as load increases and the grips open in the way they were designed to. This behaviour is presumed to result from the necessary machining tolerances that must be incorporated into the grips to ensure they will fit together and the specimen can be easily mounted. Upon loading, the specimen bends out of its arc of curvature slightly as the slack from these tolerances is taken up. As a result of this the inside surface will go into tension before the outer surface and, in cyclic loading, will see a higher ΔK . Recent tests have shown that this behaviour can be reduced by inserting a narrow strip of teflon between the specimen and the grips, and straighter fatigue crack fronts can be produced.

Tests performed to date on non-hydrided and unirradiated material have revealed a few minor problems with the design. Material in this condition is essentially not notch sensitive in the centre-cracked geometry, and failure occurs by collapse of the net section, or in the case of this specimen, shear at the pin holes. In other cases, fatigue cracks have initiated at the pin holes while trying to initiate fatigue cracks from short, shallow surface notches. The ASTM designation E338-81 in Sharp Notch Tension Testing of High-Strength Sheet Materials recognizes this problem and suggests the use of reinforcing plates around the pin hole. Along these lines the "L-shaped" plates on the grips ("e" in Figure 4) were re-machined with a serrated surface that digs into the specimen surface when the loading pins are tightened down. This arrangement redistributes the load away from the pin-holes and has proven to be very successful. Another approach that has been successfully applied to surface cracked specimens is simply to reduce the mid-section width of the specimen and thus increase the net section stress in the notch region. If this approach were to be used regularly, the grips would probably also be modified to insure that the specimen is supported equally by each grip half. This is currently only true for a specimen 60 mm wide.

One of the main advantages of this specimen design is the opportunity to test surface cracks. The problem of assessing safety margins in the presence of surface cracks and irregularly shaped cracks exhibiting extensive tunnelling is becoming quite important. Currently this specimen is being used to perform calibrations to use the potential drop technique to monitor the depth of part-through cracks in a full sized burst-test specimen. This specimen may also eventually be used to test material containing hydride blisters.

7.0 DIRECTION OF FUTURE WORK

A remaining problem to be addressed with this specimen will be to determine elastic-plastic resistance curves to characterize stable crack extension for the centre-cracked geometry. Traditionally, these resistance curves have been based on the J-integral. A brief description of the method applied to CANDU pressure tubes is given in /9/. Critical crack length is determined from the point of tangency of the experimentally derived J_R -curve and a theoretical crack driving force curve for the pressure tube.

However, it is now well understood that resistance curve shape is dependent upon specimen geometry/10/. Resistance curves generated using specimens in which the crack tip is essentially loaded in tension, such as the centre-cracked-tension (CCT) or single-edge-notch-tension (SENT) specimens, are steeper than resistance curves generated using specimens in which the crack tip is primarily loaded in bending, such as the compact-tension (CT) or three-point-bend (TPB) specimens. This observation is generally attributed to a deviation from so-called "intrinsic" R-curve behaviour/11/, brought about by the gradual loss of dominance of the HRR singularity in the crack-tip stress-strain field due to extensive deformation occurring along the 45° shear bands emanating from the crack tip. The implication of this is that J-dominance of the crack-tip field is lost and single parameter (i.e., J) characterization of the field under stable crack growth is not possible unless stringent specimen size requirements are met/12,13/. Currently, it is recommended that the ratio of the specimen ligament length to the ratio of J/σ_y , where σ_y is the yield stress, be at least 200 for a centre-cracked specimen but only 25 for a compact-tension specimen. Thus, a CCT specimen must be much larger than a CT specimen to generate an equivalent valid result.

An additional complicating factor that has not yet been properly addressed, is the likelihood that a crack in a pressure tube may not be amenable to single-parameter J characterization. Since an axial crack in a pressure tube is essentially loaded in tension by the hoop stress (the longitudinal stress has been shown to have no effect) it is possible that the HRR singularity does not dominate the crack-tip stress-strain field beyond certain limits. In this case, the significance of the measured J value is not clear. For this reason, it is possible that future work on resistance curves for pressure tubes and specimens with the centre-cracked geometry will rely on crack opening displacement (COD) as a characterizing parameter.

8.0 CONCLUSIONS

- (1) A new type of small fracture toughness specimen that maintains the original curved geometry of a CANDU pressure tube and permits a double-ended axial defect to be tested has been introduced.
- (2) Finite element analysis indicates that the mode I linear elastic stress intensity factor (K_I) relation for the curved centre cracked specimen is very similar to that theoretical relationship of a similar sized flat plate in tension.
- (3) An experimental compliance calibration has shown that the K relationship for the curved specimen is similar to the theoretical relationship for a flat plate, at least for intermediate crack length ratios ($0.5 \leq 2a/W \leq 0.65$).
- (4) Further development will be required before this specimen can be applied in situations where elastic-plastic conditions prevail at the crack tip.

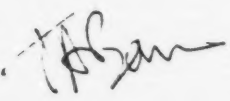
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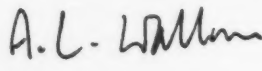
The contents of this report were also the subject of an M.A.Sc. thesis by the author. The support of Atomic Energy of Canada Ltd. during the early stages of this work, including the finite element analysis, is gratefully acknowledged. Tech-

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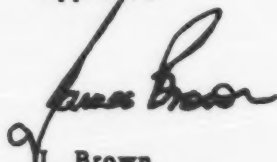
Reviewed:

Prepared:


J.A. Baron
Section Head
Nondestructive and Fracture
Evaluation Section


A.C. Wallace
Engineer
Nondestructive and Fracture
Evaluation Section

Approved:


J. Brown
Manager
Metallurgical Research Dept

ACW:SEH

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TABLE 1 - Finite Element Stress Intensity Factor Estimates

2a/W	Load (kN)	K _I (MPa√m)	
0.2	14.706	8.64	+ 0.12
	28.829	17.07	+ 0.28
	42.848	25.51	+ 0.44
	55.208	32.93	+ 0.65
	65.799	39.33	+ 0.88
	75.212	45.08	+ 1.13
	82.652	49.48	+ 1.39
0.4	13.588	12.38	+ 0.12
	26.616	24.71	+ 0.24
	39.799	36.74	+ 0.23
	52.175	48.42	+ 0.06
	62.605	58.37	+ 0.03
	72.338	68.21	+ 0.15
	80.364	76.66	+ 0.31
0.5	12.724	13.96	+ 0.26
	25.251	27.80	+ 0.47
	37.517	41.65	+ 0.57
	49.686	55.11	+ 0.57
	59.641	67.13	+ 0.93
	69.189	79.01	+ 1.57
	77.544	90.34	+ 2.21
0.6	11.757	15.41	+ 0.34
	23.199	30.72	+ 0.63
	34.600	45.98	+ 0.77
	45.996	61.38	+ 1.08
	55.826	75.89	+ 1.91
	64.619	90.25	+ 3.31
	72.331	105.10	+ 5.14
0.8	9.126	18.63	+ 0.44
	18.007	37.12	+ 0.78
	26.926	55.64	+ 0.98
	35.466	74.97	+ 1.97
	42.998	95.75	+ 4.45
	47.931	115.27	+ 3.99
	50.244	149.78	+ 16.54

TABLE 2 - Experimental Compliance Data

Specimen I.D.	Normalized Crack Length (2a/W)	Normalized Compliance (EBC)
#1	.154	.2789
	.277	.4499
	.289	.4826
	.322	.5399
	.364	.6041
	.396	.6503
#2	.167	.2642
	.236	.3881
	.283	.4867
	.342	.5980
	.409	.7292
	.509	.8908
#3	.604	1.1567
	.166	.2769
	.376	.6773
	.468	.8393
	.551	1.0491
	.617	1.2409
	.694	1.5092
	.759	1.7988

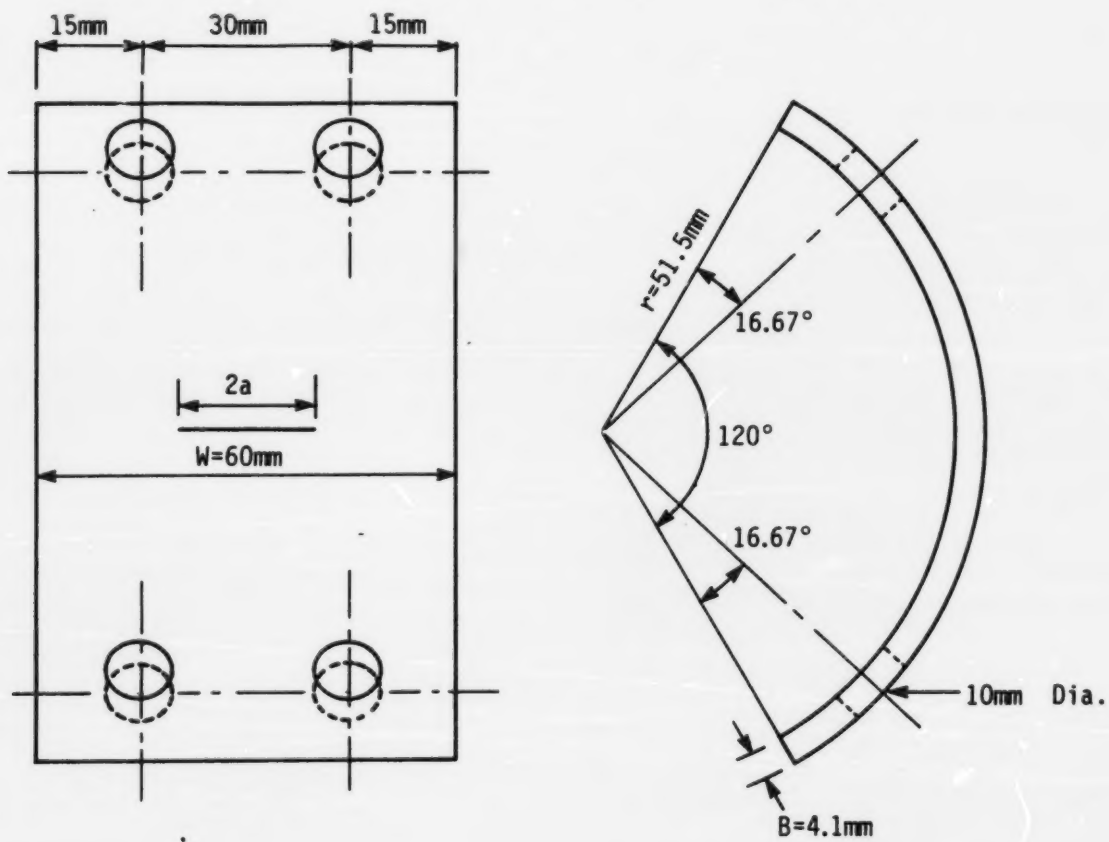


FIGURE 1
CURVED CENTRE CRACKED SPECIMEN

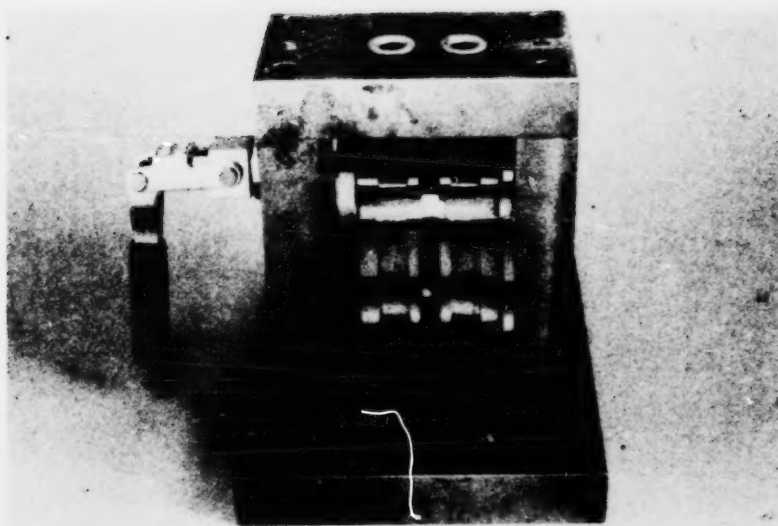
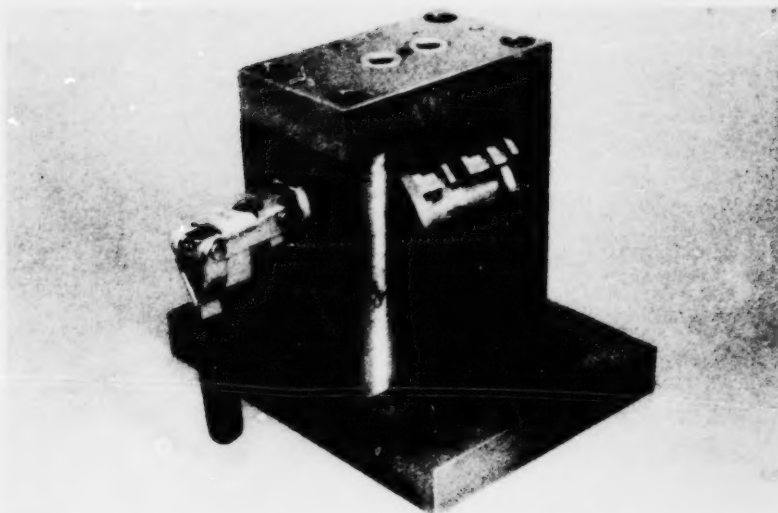


FIGURE 2
2 VIEWS OF DRILLING JIG USED TO PRECISELY
POSITION HOLES IN THE CURVED SPECIMEN

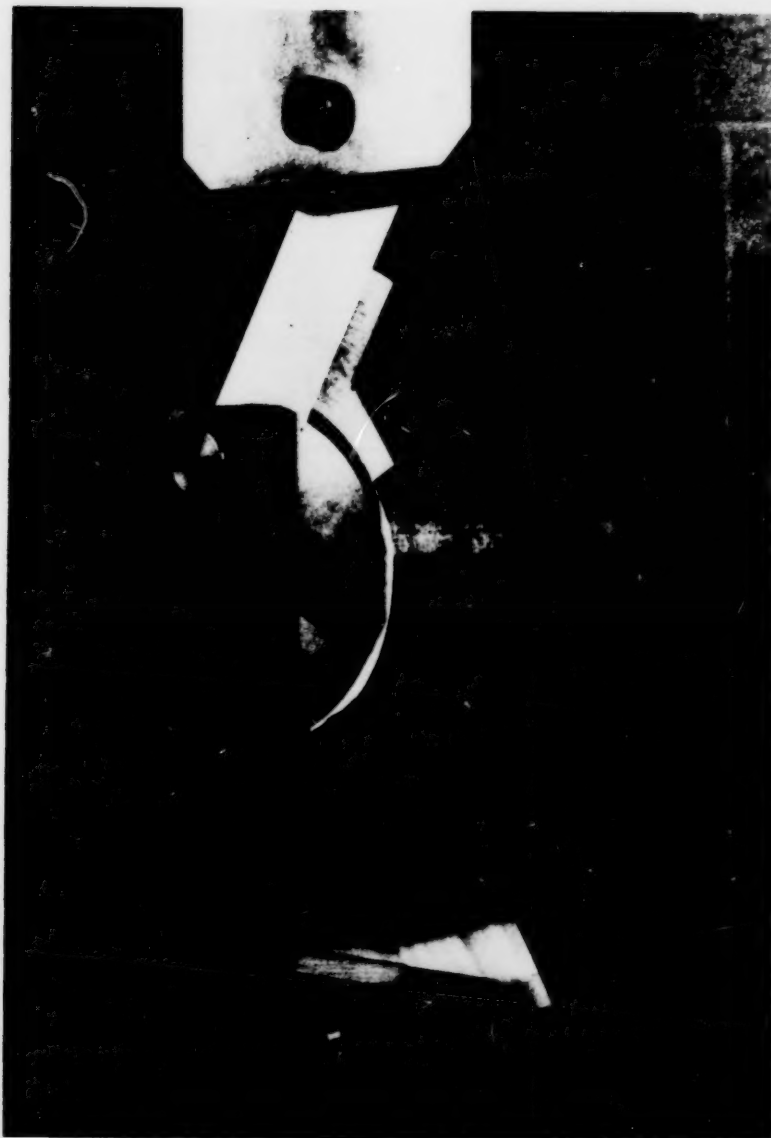


FIGURE 3
VIEW OF AN UNNOTCHED SPECIMEN
MOUNTED IN THE GRIPS

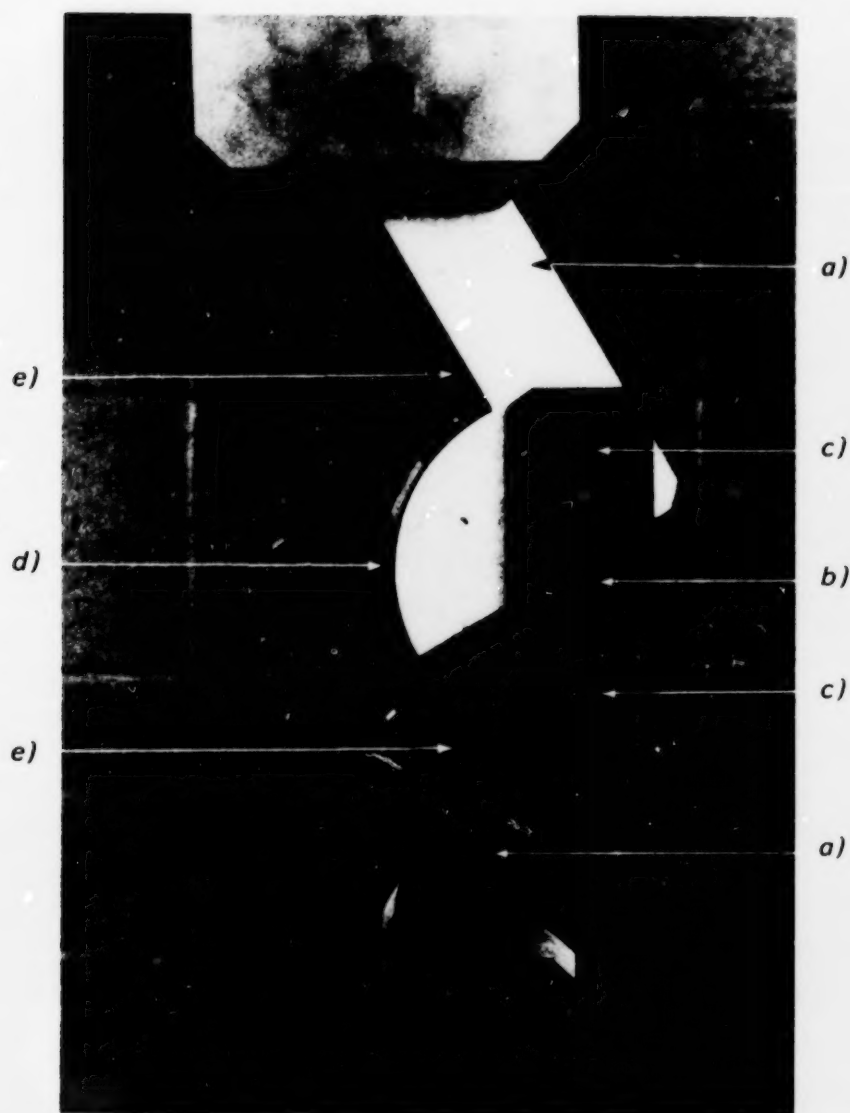


FIGURE 4
SIDE VIEW OF SPECIMEN MOUNTED IN GRIPS
WITH VARIOUS COMPONENTS IDENTIFIED

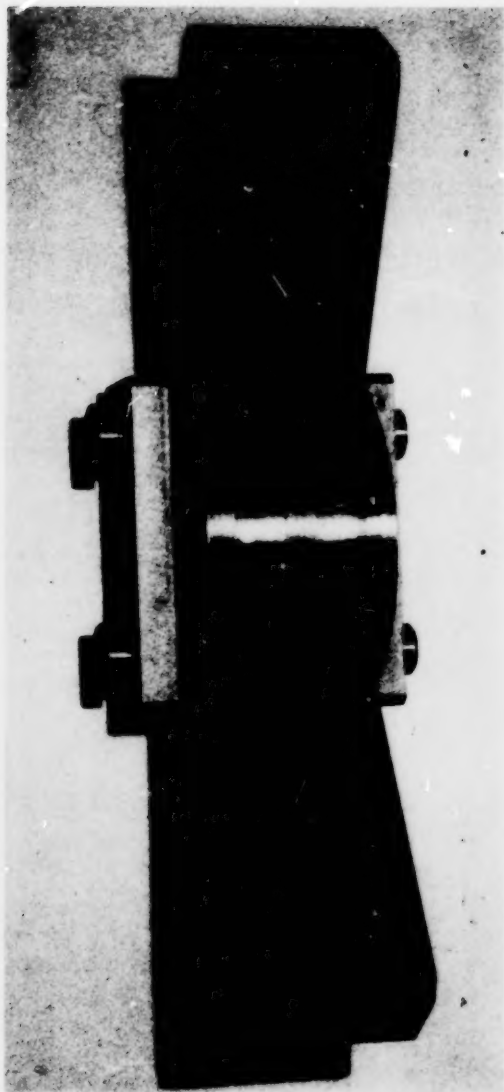


FIGURE 5
GRIPS IN THEIR INITIAL
CLOSED POSITION

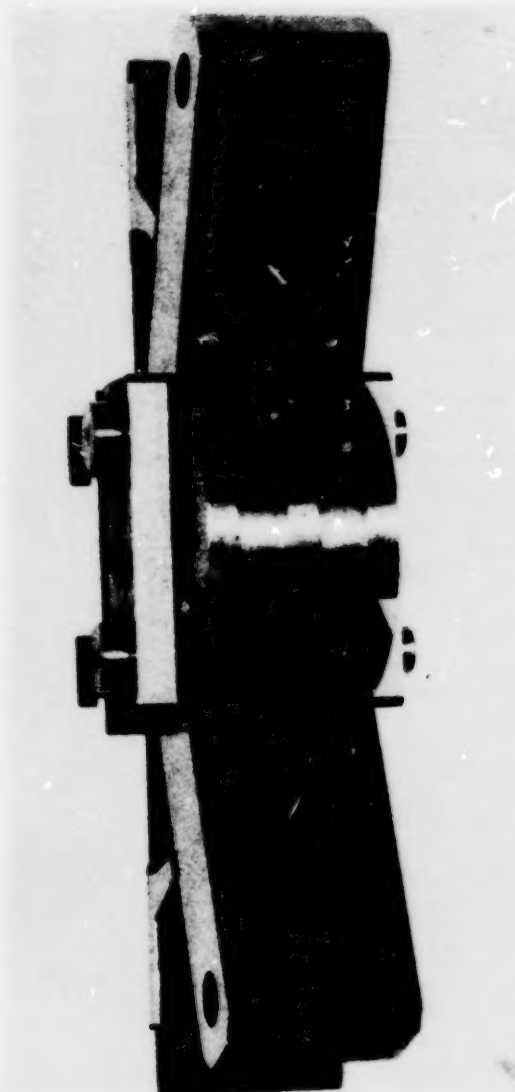


FIGURE 6
GRIPS AFTER
OPENING UNDER LOAD

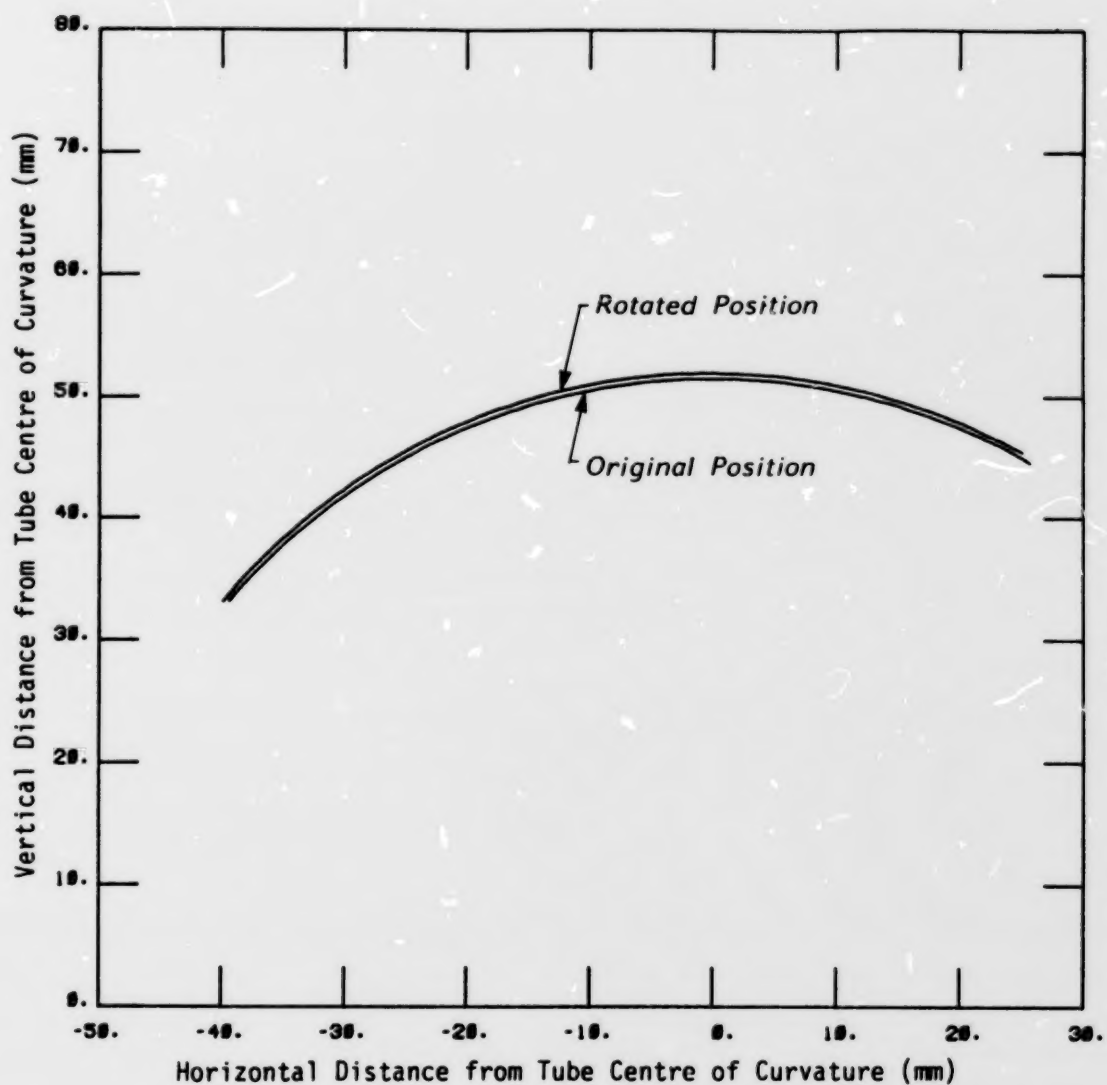


FIGURE 7
DEFORMATION ANALYSIS FOR GRIP-HALF ROTATION OF 0.8°

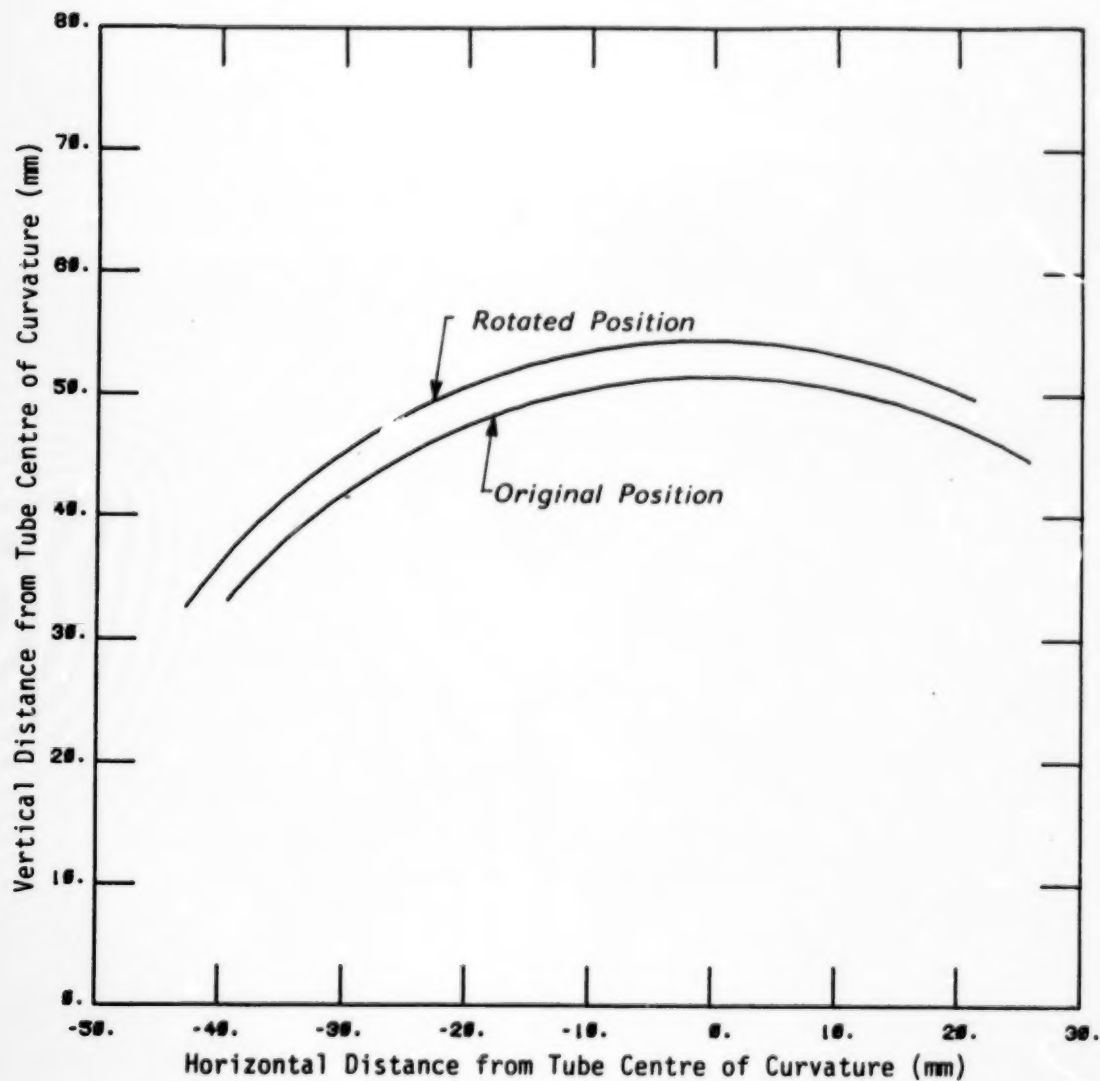


FIGURE 8
DEFORMATION ANALYSIS FOR GRIP-HALF ROTATION OF 5°

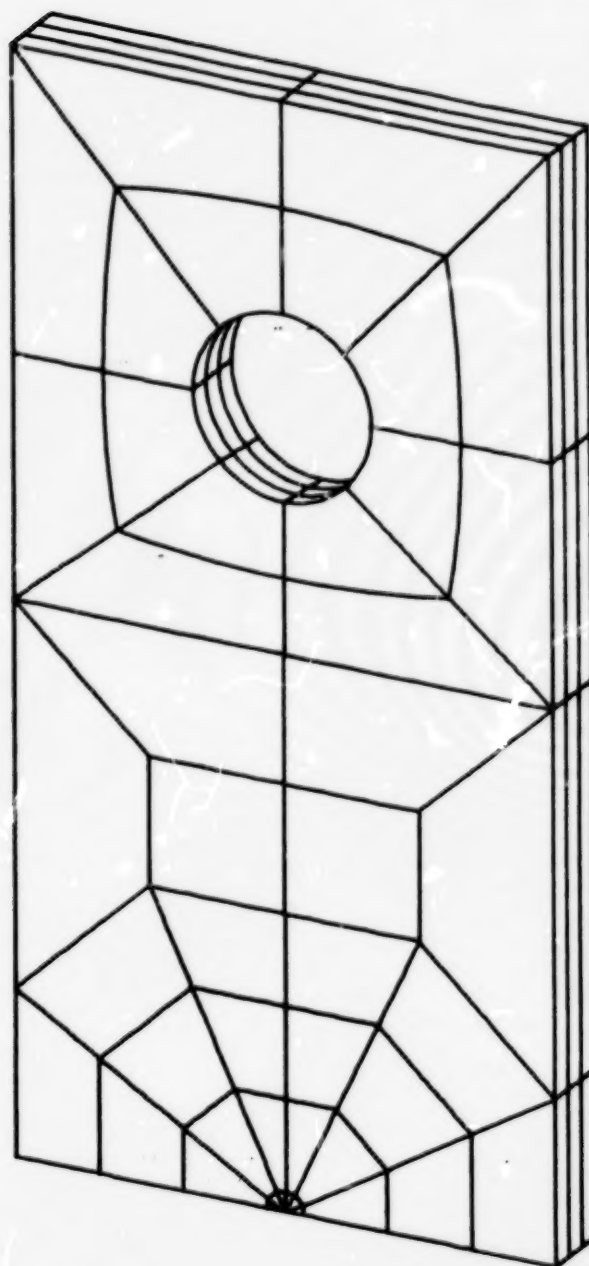


FIGURE 9
FLAT SPECIMEN MESH FOR $2a/W = 0.5$

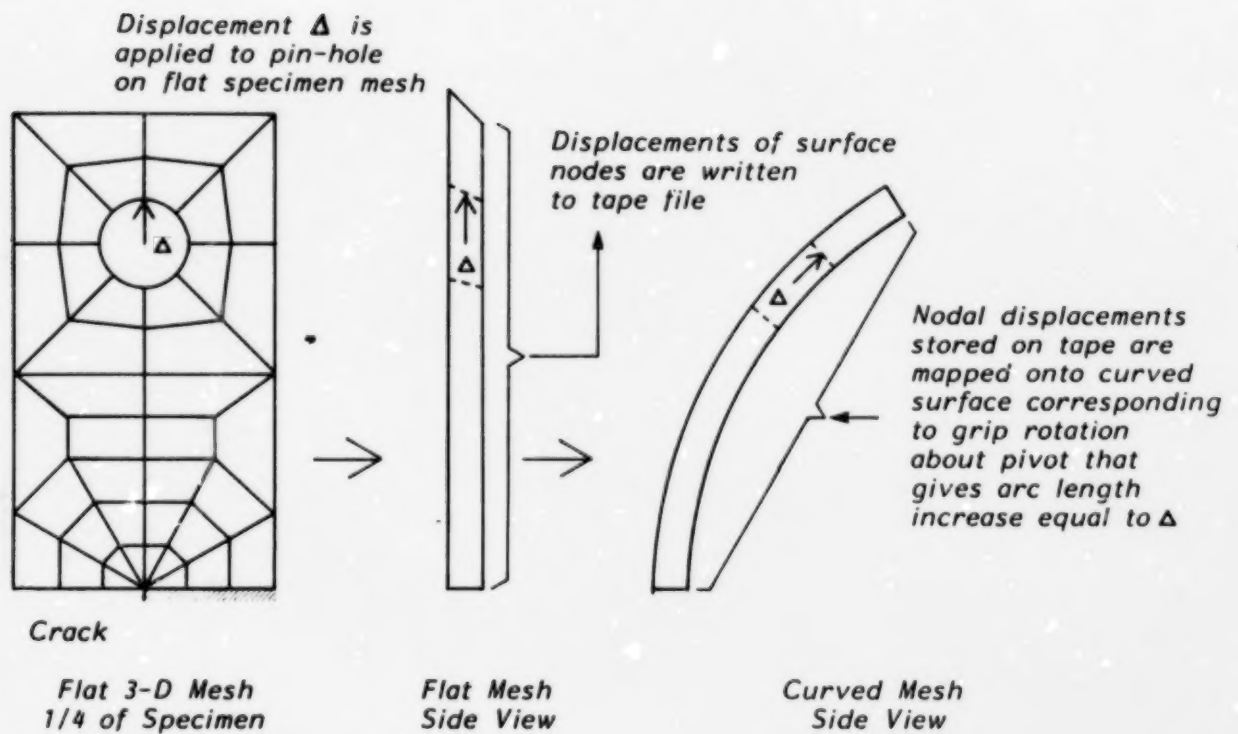


FIGURE 10
ILLUSTRATION OF MAPPING OF FLAT SPECIMEN MESH ONTO
CURVED GEOMETRY AND TRANSFER OF INSIDE SURFACE NODAL
DISPLACEMENTS BETWEEN GEOMETRIES

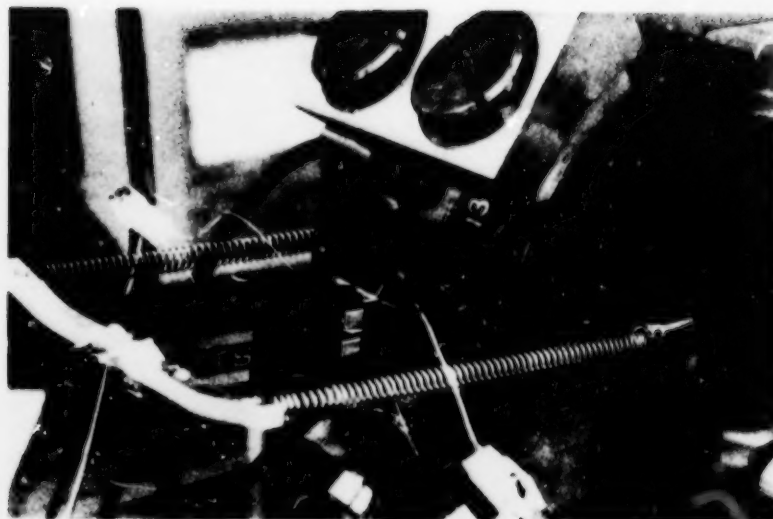


FIGURE 11
VIEW OF EXTENSOMETER USED FOR DISPLACEMENT
MEASUREMENTS, (THE SPECIMEN SHOWN DIFFERS FROM
THOSE USED IN THE COMPLIANCE CALIBRATIONS)

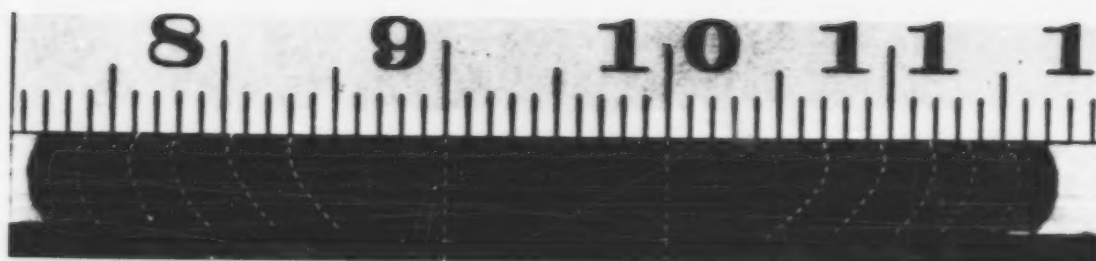
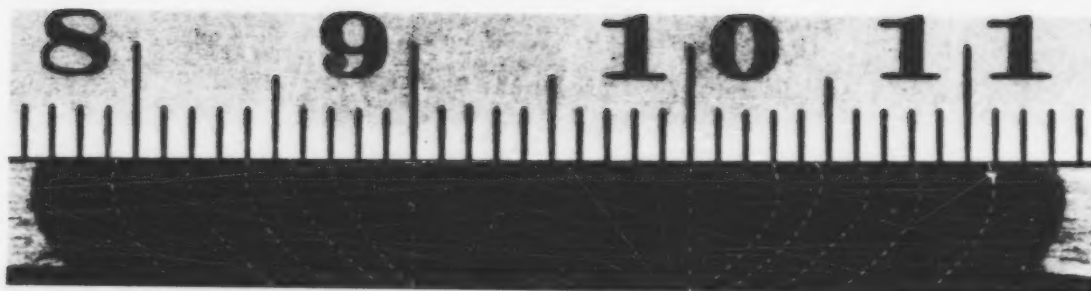


FIGURE 12

FRACTURE SURFACES OF TWO OF THE CALIBRATION SPECIMENS SHOWING TENDENCY FOR SKEWED CRACK FRONTS AT SHORTER CRACK LENGTHS. THE SCALE IS IN cm AND IS ADJACENT TO THE SPECIMEN INSIDE SURFACE. CRACK FRONTS AT EACH HEAT TINT BAND HAVE BEEN HIGHLIGHTED FOR BETTER VISIBILITY.

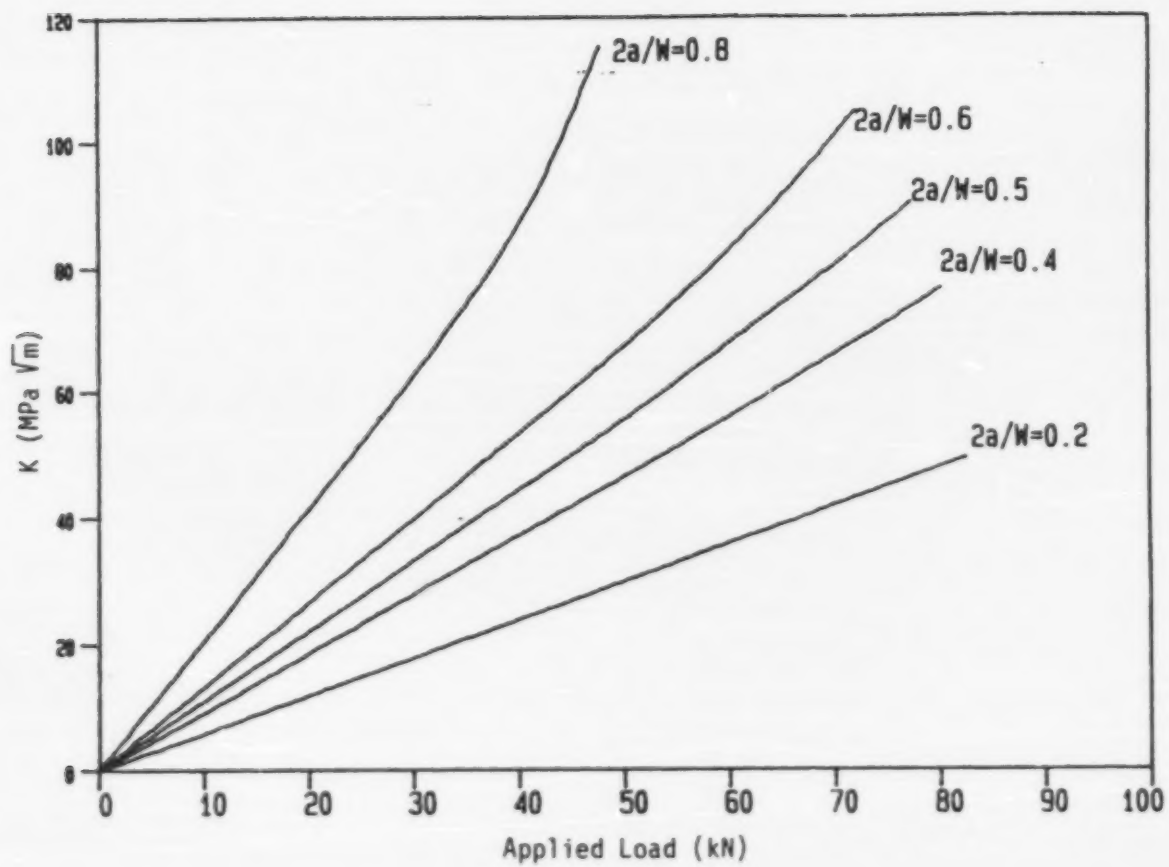


FIGURE 13
FINITE ELEMENT PREDICTIONS OF K VERSUS
APPLIED LOAD FOR DIFFERENT CRACK LENGTH RATIOS ($2a/W$)

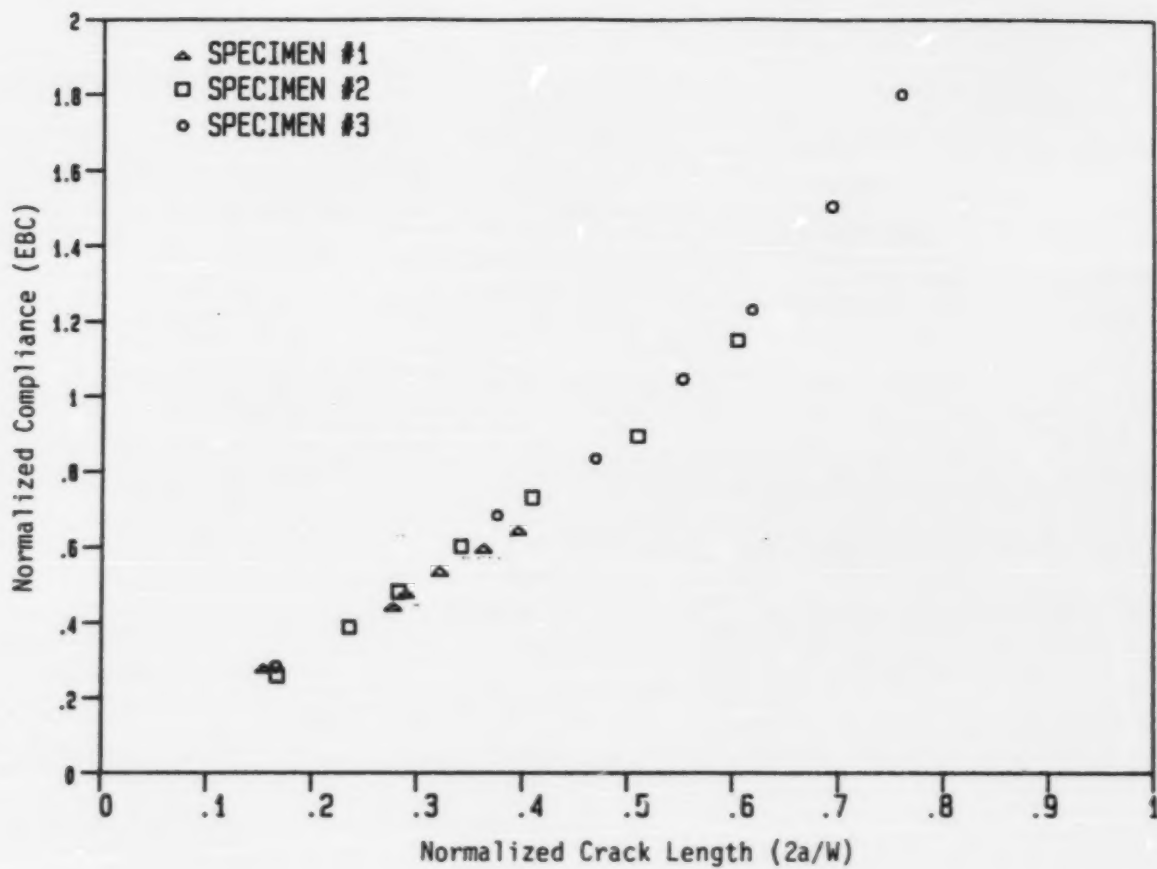


FIGURE 14
COMPLIANCE DATA FROM 3 TEST SPECIMENS

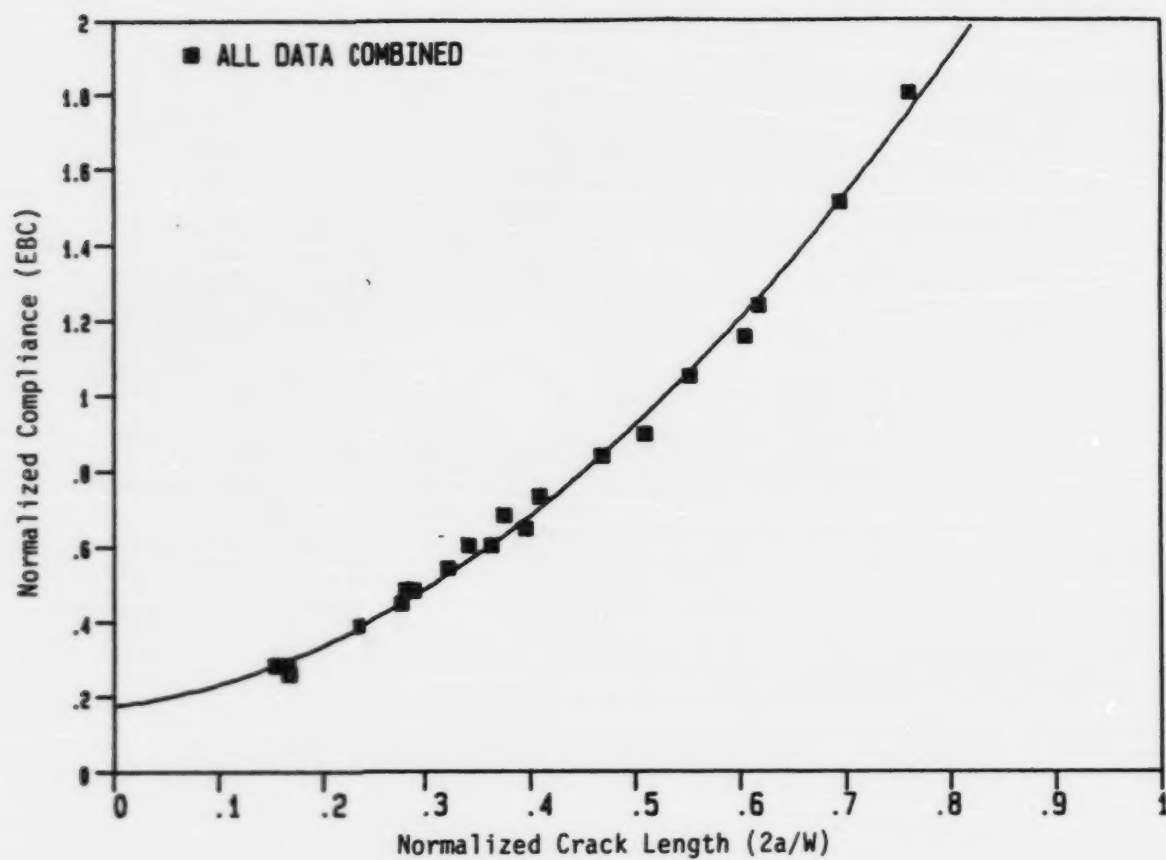


FIGURE 15
CURVE REPRESENTING SECOND DEGREE POLYNOMIAL FIT TO
COMPLIANCE DATA FROM 3 SPECIMENS IN FIGURE 14

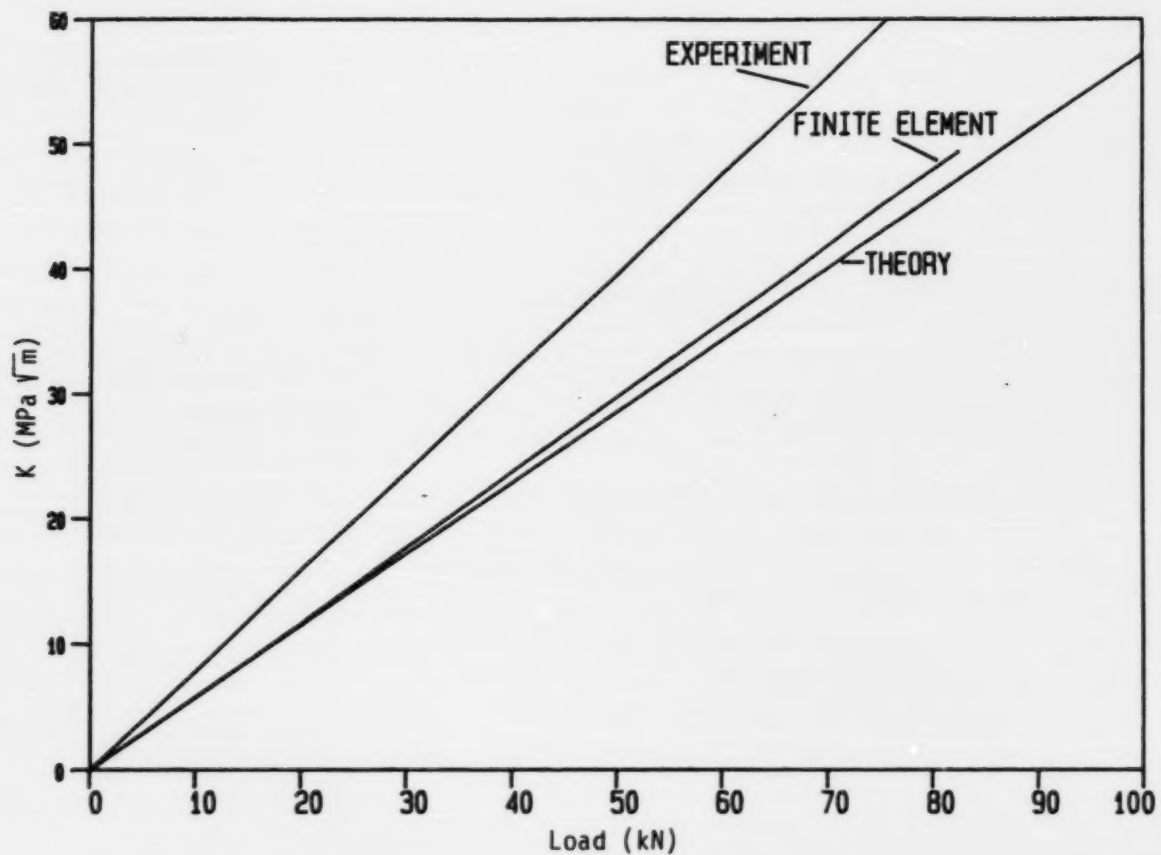


FIGURE 16
COMPARISON OF K VALUES OBTAINED FROM EXPERIMENTAL COMPLIANCE,
FINITE ELEMENT ANALYSIS AND THEORETICAL FLATE PLATE
EQUATION FOR $2a/W=0.2$

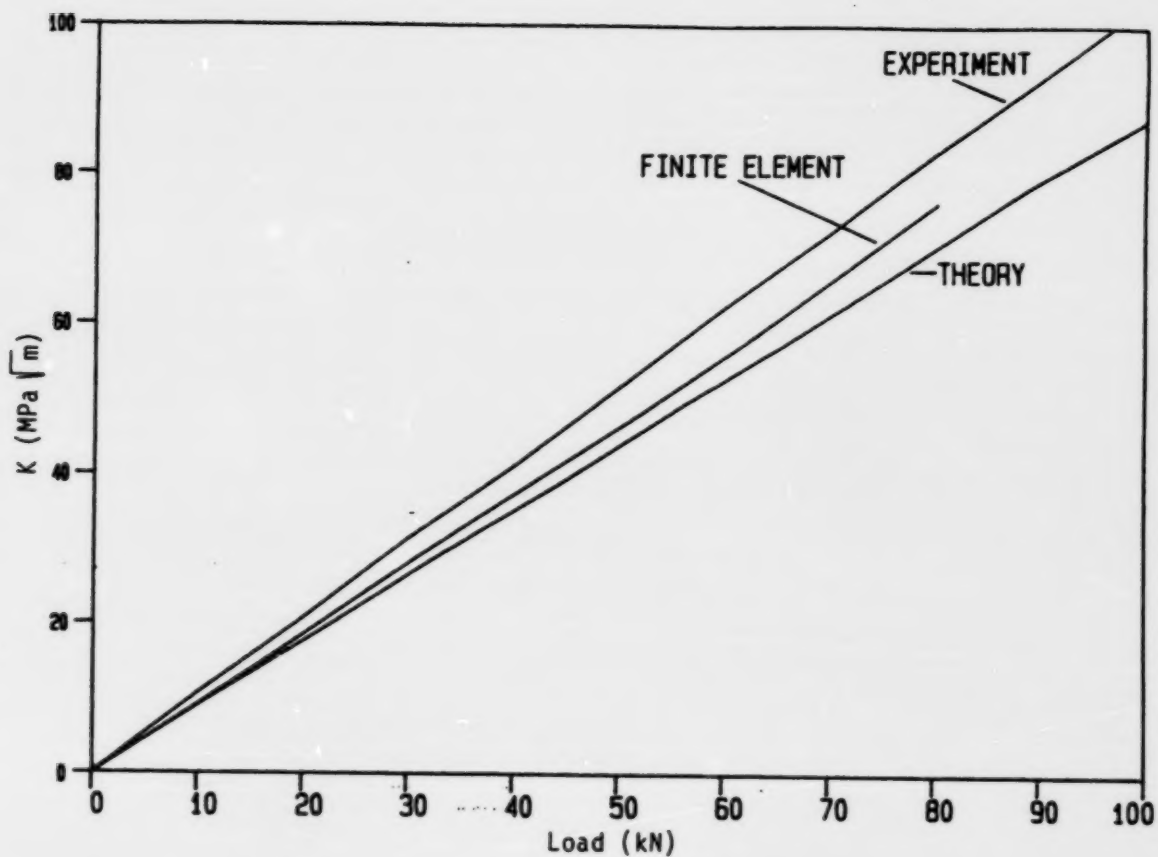


FIGURE 17
COMPARISON OF K VALUES OBTAINED FROM EXPERIMENTAL COMPLIANCE,
FINITE ELEMENT ANALYSIS AND THEORETICAL FLAT PLATE
EQUATION FOR $2a/W = 0.4$

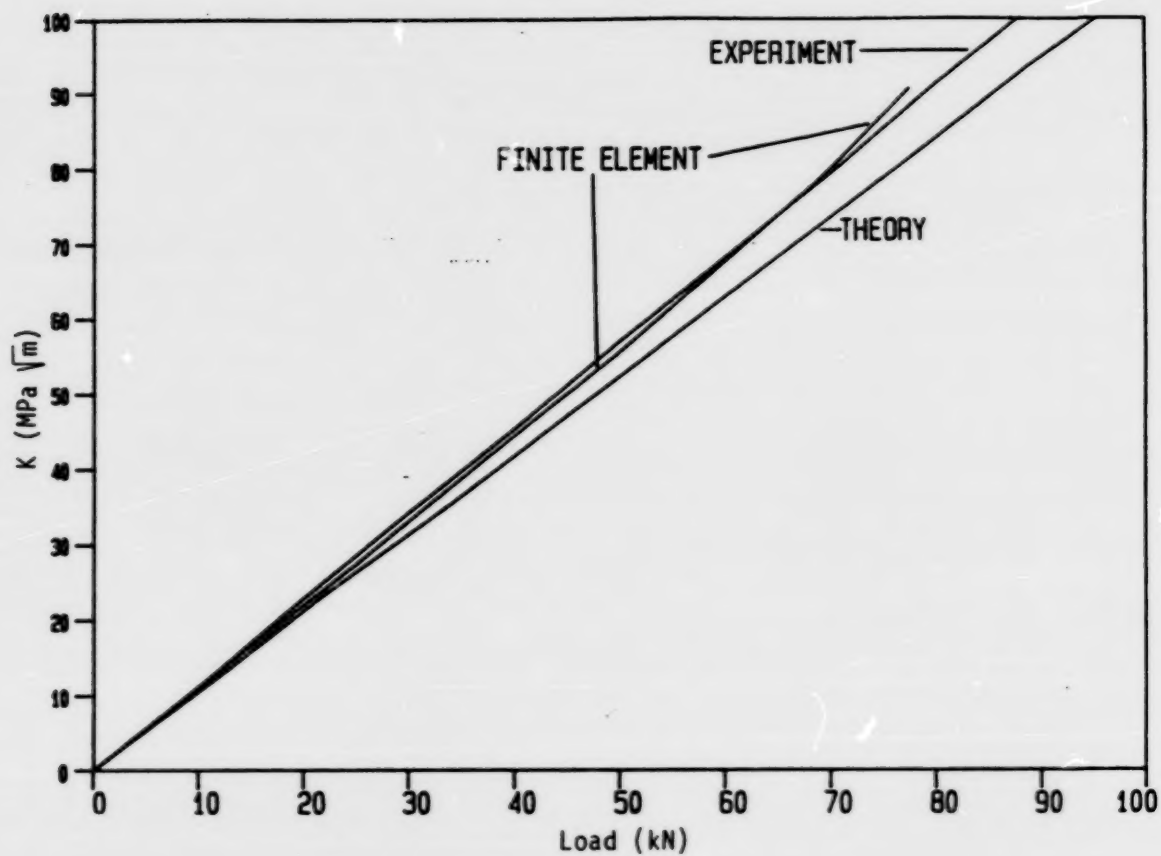


FIGURE 18
COMPARISON OF K VALUES OBTAINED FROM EXPERIMENTAL COMPLIANCE,
FINITE ELEMENT ANALYSIS AND THEORETICAL FLAT PLATE
EQUATION FOR $2a/W = 0.5$

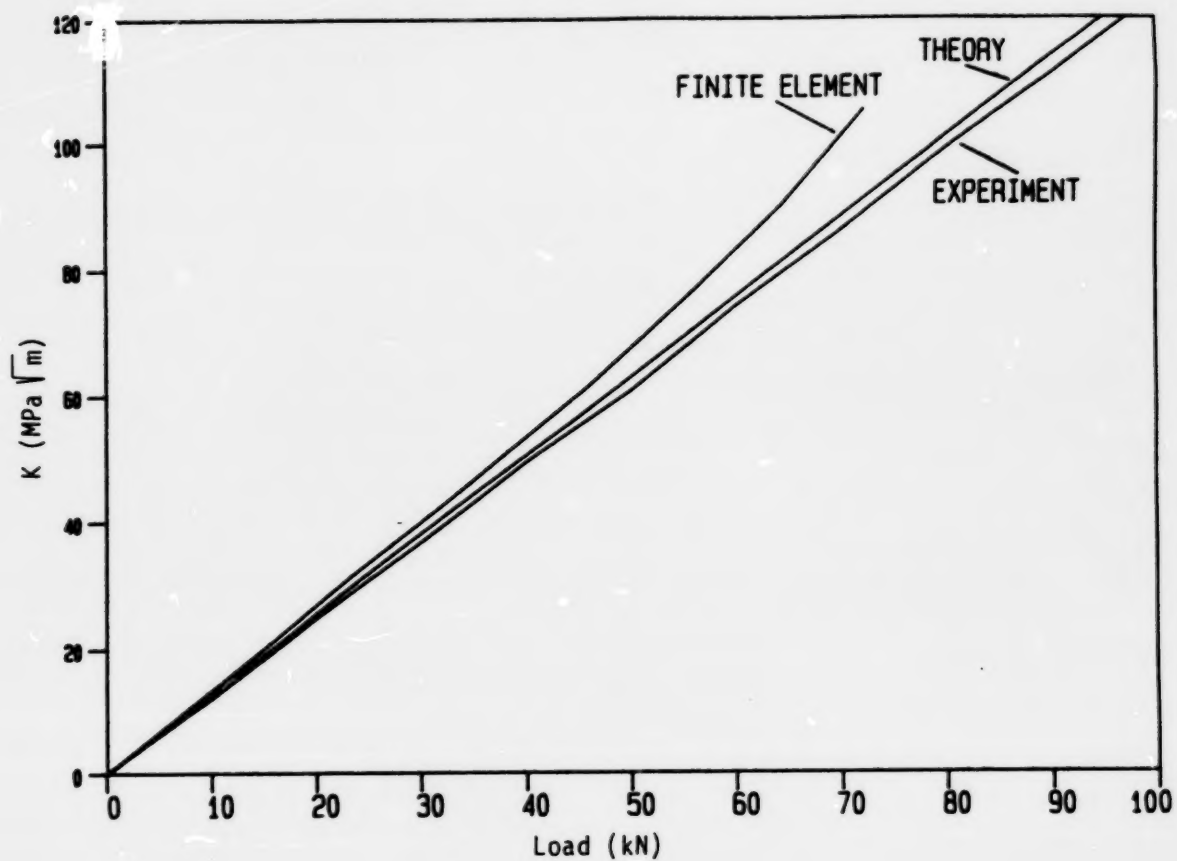


FIGURE 19
COMPARISON OF K VALUES OBTAINED FROM EXPERIMENTAL COMPLIANCE,
FINITE ELEMENT ANALYSIS AND THEORETICAL FLAT PLATE
EQUATION FOR $2a/W = 0.6$

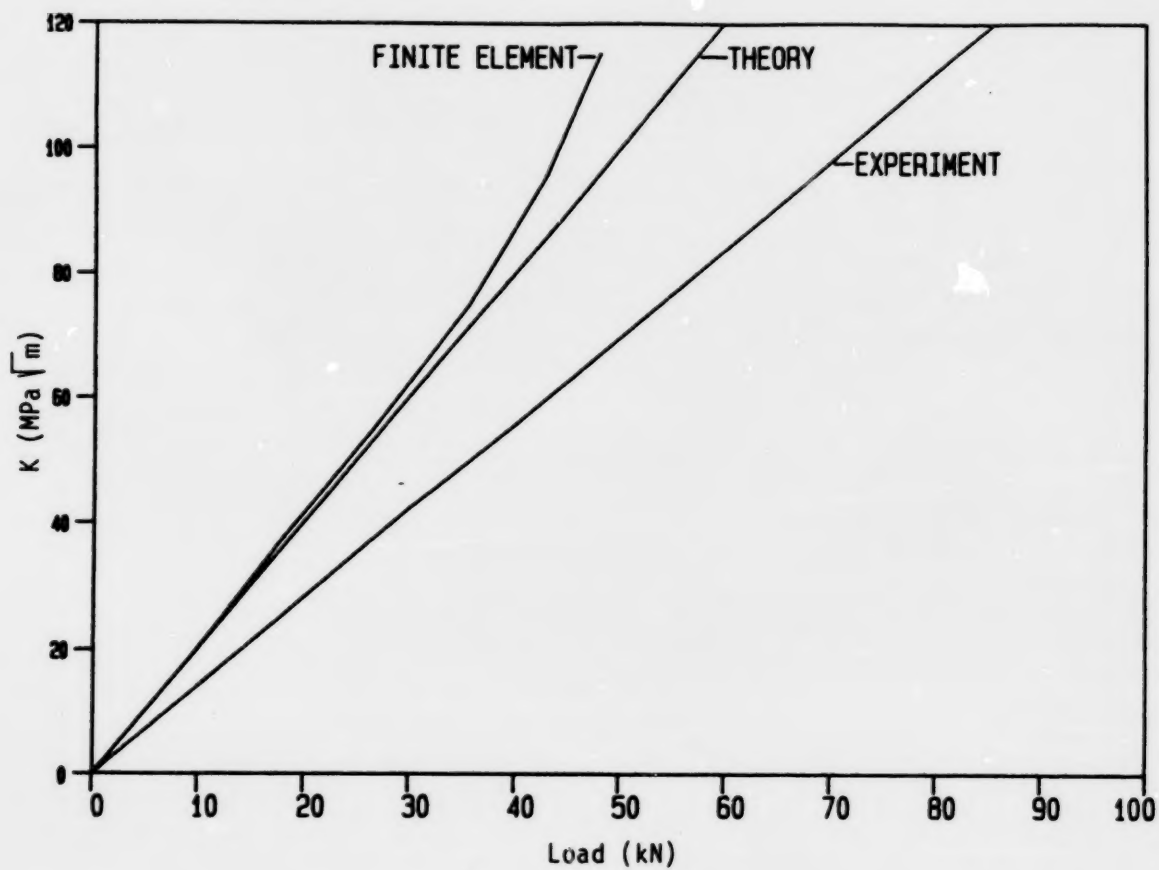


FIGURE 20
COMPARISON OF K VALUES OBTAINED FROM EXPERIMENTAL COMPLIANCE,
FINITE ELEMENT ANALYSIS AND THEORETICAL FLAT PLATE
EQUATION FOR $2a/W = 0.8$

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